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Shear and Moment Strength of a Composite Concrete Beam

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Abstract**—***Composite concrete beams construction separate widely in buildings and bridges for economical purposes. Some international specifications and codes present design rules to predict nominal shear and flexural strength for a composite concrete beam, one of them is ACI 318M-14. The contributions of the concrete slab and composite action to the vertical shear and moment strength of composite concrete beams are not considered in current design specifications and codes. In this paper, a comparative study deals with shear and bending moment capacity and shear stress of composite concrete beams is presented. The work includes a comparison between experimental tests results, ACI 318M-14 nominal shear and flexural strengths and finite element results. The ACI 318M-14 failed to predict the ultimate capacities, while the finite element analysis results compare satisfactorily with the experimental ones.*

Keywords**—** *Composite beam, design provision, interface, moment strength, shear strength.*

I. Introduction

Composite construction consists of two or more materials combined together in one structural unit and uses each material through its best advantage. The number of combinations is in continuous increase; steel and concrete, timber and steel, timber and concrete, two concretes cast at different times, etc.

The composite concrete beam is actually a built-up member, using two concretes having different ages and using each one to its best advantage. A typical composite concrete beam consists of three parts: the structural reinforced concrete precast beam, the reinforced concrete slab that is casted later, and some type of shear connectors between the beam and slab to hold the two parts together.

Fig. 1 shows different types of composite concrete beam sections. Primarily because of the better quality control of a precast unit, it is usually economical to use higher concrete strength for the precast beam than for the cast-in-place slab (or deck).

The most important aspect of the joining of two concretes is the strength of the bond that can be achieved. This bond is crucial, as it determines what forces can be transferred across the junction between the two concretes [Cheong and MacAlerey, 2000].

In building constructions, where most loads are primarily static, the natural bond between the concrete beams and slab provided a valuable reserve of strength. In bridge constructions, the moving and impact loads possibly terminate the natural bond after a very few load cycles.

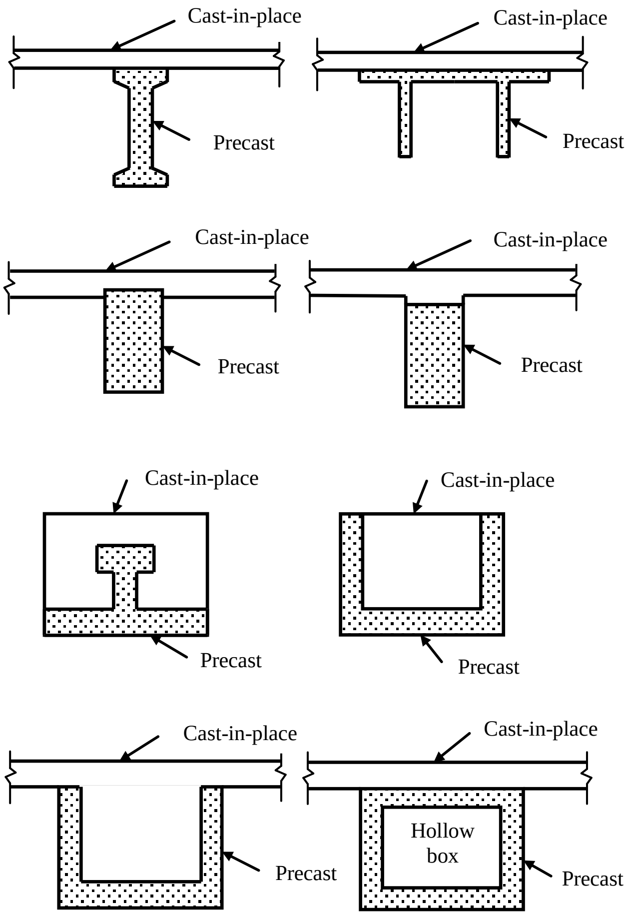

Fig. 1. Different types of composite concrete beam sections.

Johnson (1975) discussed the behavior of two types flitched beams; beams with no shear connectors with full slip and beams with shear connectors with no slip (i.e., full interaction), as shown in Figure (2). It may be shown that the maximum bending stress is reduced by 50% by net, providing shear connection, while the maximum shearing stress is unchanged. Also, the mid-span deflection with fully effective shear connectors (no slip at the interface) is 25% of that in the case with no shear connectors (in this special case). Thus the provision of shear connectors increases both the strength and stiffness of a beam of given size, which leads to a reduction in the beam size for a given loading.

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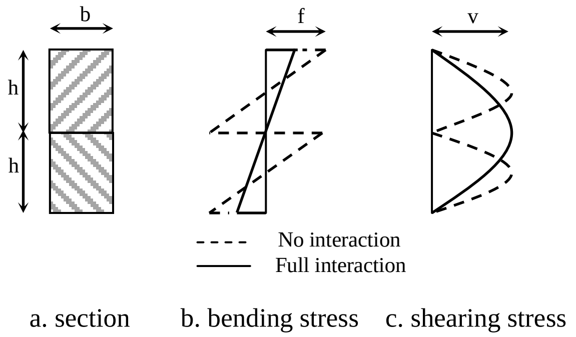

Fig. 2. Slip and partial interaction for two rectangular beams (Johnson, 1975).

In actual practice with a composite concrete beam and slab construction, no composite action is impossible because there are always some degrees of bond and friction between the slab and the beam. Similarly, full composite action is impossible because there is always some small degree of slip, no matter how rigidity the shear connection may be designed [Al-Sherrawi, 2000].

Fig. 3 shows the strain diagram in a composite concrete beam with different types of interaction. It can be seen that for the case of no interaction, each of the beam and slab acts separately (Fig. 3-a). While the composite beam with full interaction behave as a single monolithic beam (Fig. 3-c). The behavior of a partially composite beam is in between (Fig. 3-b).

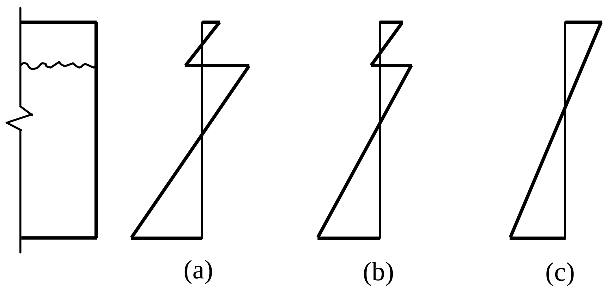

Fig. 3. Strain diagrams in (a) noncomposite, (b) partially composite, (c) full composite beam.

The evaluation of the strength of the joint between the precast concrete beam and the cast-in-place concrete slab has been the subject of considerable research. When the joint in a composite concrete beam is unable to transmit all internal forces from one part of the section to the other part in the same manner as if the entire section were structural concrete cast in one piece, the beam is only partially composite with stiffness characteristics between those of a fully composite and a two-piece beam.

Current design methods rely heavily on empirically derived equations, which based on experimental results of ultimate strength tests of the joint.

Different codes and specifications present rules for design of the composite concrete beam. While such design rules are adequate for many situations, on occasions a more detailed method of analysis is required, which takes account of most the principal parameters.

II. Literature Review

Several experimental investigations of composite concrete beams are done in literature. Tests were made as long ago as 1914 by Johonson and Nichols (Grossfield and Birnstiel, 1962).

Preliminary tests were made by Revesz (1953) on five different composite T-beams of 4.267 m span to destruction to observe the behavior of the beams under loads. A conclusion has been attained that the variation in the quality of the cast-in-place concrete of T-beams did not exert appreciable influence on the load capacity of composite beams.

Tests carried out by Hanson (1960) on the problem of shear connections between precast beams and cast-in-place slabs indicated that the ultimate horizontal shear strength of a smooth bonded joint was about 2.069 MPa and that of a rough bonded joint was 3.449 MPa. In addition, it was found that the shear strength of a joint could be increased approximately 1.207 MPa for each percent of reinforcing steel crossing the joint.

A pilot test program of limited scope was undertaken by Grossfield and Birnstiel (1962) to study the effect of three joint treatment methods and the problems of instrumentation.

Saemann and Washa (1964) tested 42 T-beams to provide information on several variables; Degree of roughness of contact surface, length of shear span, percentage of steel across the joint, effect of shear keys, position of the joint with respect to the neutral axis, concrete compressive strength. Results obtained indicated complex relations between roughness of surface joint, percent steel across joint, and shear span.

An investigation of the strength of the joint, between a precast concrete beam and a cast-in-place slab, when the composite beam was subjected to repeated loading, has been done by Badoux and Hulsbos (1967). Equations have been presented which yield a conservative allowable stress for the horizontal shear in composite members under repeated loads.

Loov and Patnaik (1994) investigated the horizontal shear strength of composite concrete beams with a rough interface in an effort to develop a single equation to replace the five different equations required by the ACI Building Code for determining the horizontal shear stress capacity of a composite joint.

Provisions of the American Concrete Institute's code on flexural strength, shear strength, and deflection characteristics are found by Patnaik (2001) to be satisfactory. However, the code clauses dealing with horizontal shear are found to be very conservative.

Mahmoud and Al-Sherrawi (2002) used a two-dimensional plane stress finite element procedure in the analysis of composite concrete beams under concentrated loads. Al-Sherrawi (2003) extended the work to the three dimensional modeling of composite specimens under shear force.

Kahn and Slapkus (2004) showed that the AASHTO and ACI provisions for interface shear of composite concrete beams could be applied conservatively to composite sections constructed with high strength concretes.

Kovačovic (2013) focused on the theoretical and experimental analyses of the shear resistance at an interface between precast beams and cast slab deck. The experimental part was compared to the numerical analysis performed by means of FEM basis nonlinear software.

Jiang et al. (2016) examined experimentally the shear-friction behavior of shear interface with transverse reinforcement between precast girder using high-strength concrete and cast-in-place slab with lightweight concrete. They concluded that for both sand-lightweight and normal weight cast-in-place slab concretes, the interface shear strengths predicted by the design equations given in AASHTO LRFD 2014 and ACI 318-14 are conservative.

Fang et al. (2018) tested 12 composite beams to provide experimental cases with the variables of interface preparation, clamping stress and lightweight slab concrete strength. They found that formulas especially the ones from current AASHTO and ACI design codes, give a conservative theoretical prediction of horizontal shear capacity of composite T-beams.

The comparison between the finite element idealization and the experimental results shows a good concordance within acceptable ranges (Al-Sherrawi and Mahmoud, 2018).

Despite experimental evidences, the contributions of the concrete slab and composite action to the vertical shear and moment strength of composite concrete beams are not considered in current design specifications and codes, which lead to conservative designs.

The present work is devoted to the study the ultimate shear and moment strength of a reinforced concrete composite beam under combined bending and shear. A comparative study deals with shear and bending moment capacity of composite concrete beams is presented. The work includes a comparison between experimental tests results, ACI 318M-14 nominal strengths and finite element results.

III. ACI CODE DESIGN PROVISIONS

Conventionally, a reinforced concrete beam has a nominal shear and flexural strength (V_n and M_n) as follows (ACI 318M-14):

$$V_n = V_c + V_s$$

where

$$V_c = \text{least of} \begin{cases} \left(0.16\sqrt{f_c^{'}} + 17\rho_w \dfrac{V_u d}{M_u}\right) b_w d \\ \left(0.16\sqrt{f_c^{'}} + 17\rho_w\right) b_w d \\ 0.29\sqrt{f_c^{'}}\, b_w d \end{cases}$$

$$V_s = \frac{A_v f_y d}{s}$$

and

$$M_n = \rho b d^2 f_y \left(1 - 0.59\rho \frac{f_y}{f_c^{'}}\right)$$

Where V_c and V_s are nominal shear strength provided by concrete and shear reinforcement, respectively; $\rho_w = A_s/b_w d$; M_u is the factored moment at the section; and ρ is the ratio of the reinforcement.

When a composite concrete beam bends under a load, it is assumed that the strain is linear across the beam section, zero at the neutral axis with a fixed slope to the outermost concrete fibers. The compression force must equal the tension force. In order to locate the neutral axis of that beam, the modulus of elasticity of the beam and the slab must be factored.

IV. RESULTS

Six of composite concrete beams tested by Saemann and Washa (1964) have been chosen in this study to compare the ultimate shear and moment strength gotten from the experimental work with design provisions of ACI 318M-14 and finite element analyses results made by Mahmoud and Al-Sherrawi (2002). Table I lists concrete strength and reinforcement across the interface in these beams.

TABLE I. Beams properties.

Beam		Steel across joint (%)	f_c' (MPa)	
No.	Series		Web	Slab
10	A	1.02	21.1	19.8
5	C	0.51	20.8	22.5
5	D	0.20	23.4	24.7
12	C	0.11	20.6	23.9
14	C	0.06	21.6	19.8
16	C	0.00	20.9	21.1

Fig. 4 - 6 show a comparison between the ultimate shear strength, moment strength and shear stress, respectively, according to the experimental, the finite element, and the ACI Code results when changing the percentage of steel across the joint.

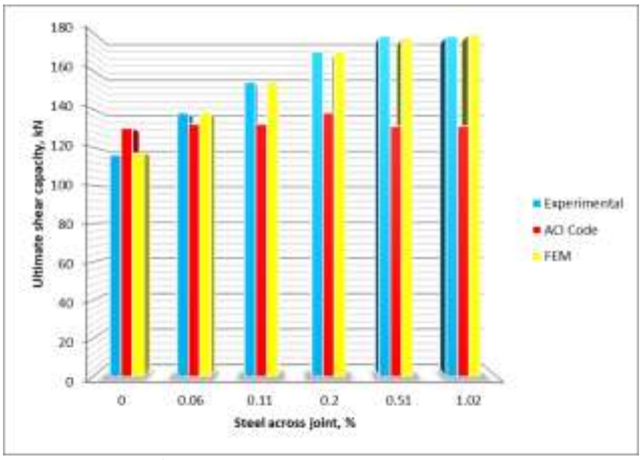

Fig. 4. Variation of ultimate shear capacity with steel percentage across the joint.

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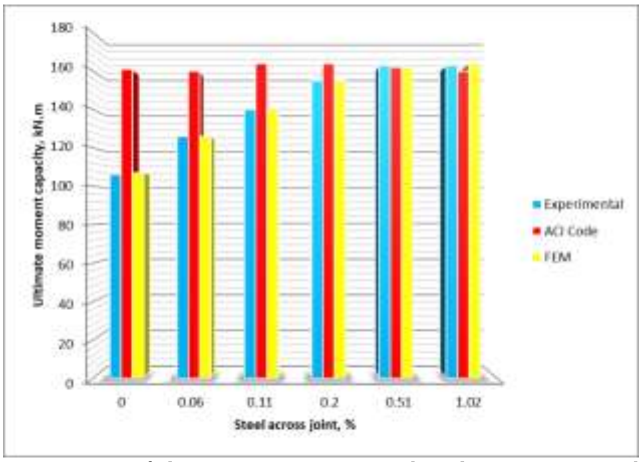

Fig. 5. Variation of ultimate moment capacity with steel percentage across the joint.

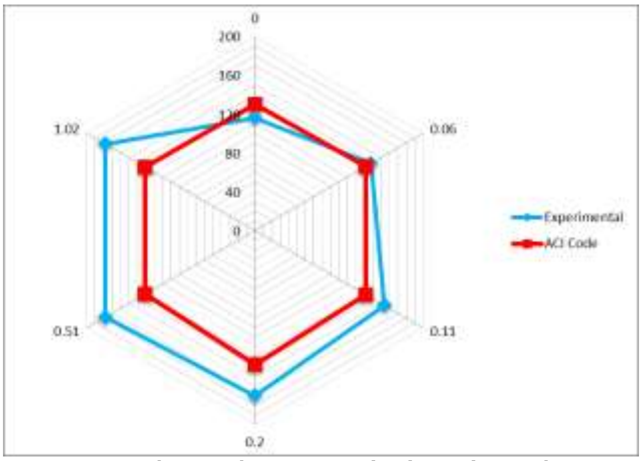

Fig. 7. Comparison between the experimental and ACI ultimate shear strength with steel percentage across the joint.

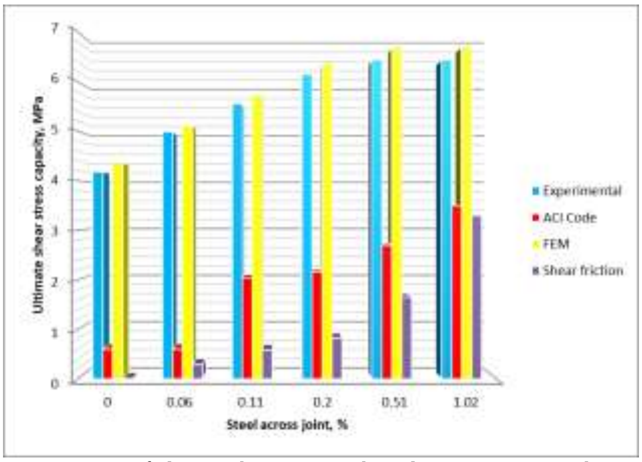

Fig. 6. Variation of ultimate shear stress with steel percentage across the joint.

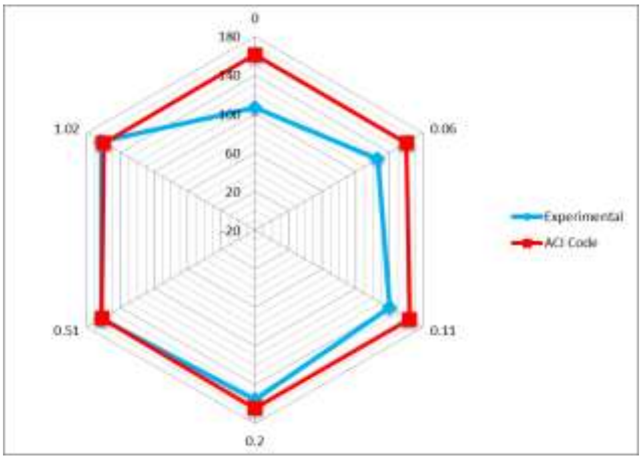

Fig. 8. Comparison between the experimental and ACI ultimate bending moment strength with steel percentage across the joint.

Several important observations may be made from Figs. 4 - 6, which show clearly that the ultimate shear and flexural capacities, of a composite concrete beam, increase as the steel percentage across the joint (shear connectors), between the precast web and the cast-in-place slab, increases. These increases diminish as the steel percentage becomes more than 0.50% from the contact area between the two elements. Also, the ACI Code failed to predict the ultimate capacities in shear and bending for a composite beam, this may be due to neglecting the effect of partial action.

Figs. 7 and 8 present radar Comparison between the experimental and ACI ultimate shear strength and bending moment strength, respectively with steel percentage across the joint. It's clear that ACI 318M-14 is almost conservative in predicting shear strength, while it gives overestimating bending moment strength values for steel percentage less than 0.50% from the contact area between the beam and the slab.

Table II shows a comparison in the ultimate shear force for the beams 16C and 10A with different provided stirrups. It can be shown that the ACI Code gives different values compared with the predicted in this study.

TABLE III. Comparison in ultimate shear force.

Beam	Provided stirrups	Ultimate shear force (kN)		
		ACI	**Exp.**	**FEM**
16C	Full stirrups	130	116	117
	Without cage stirrups	109	---	117
	Without stirrups	34	--	93
10A	Full stirrups	131	178	179
	Without cage stirrups	131	--	145

V. CONCLUSION

The following conclusions can be drawn from the present study:

1. The ACI 318M-14 failed to predict the ultimate capacities in shear and bending for a composite concrete beam.
2. The steel percentage of 0.50% from the contact area is adequate.

3. Finite element analysis can be used to study composite concrete beams.

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